best fiducial mark in the He^5 spectrum is the $\frac{3}{2}^+$ state at 16.69 Mev, which happens to be very close to the triton-plus-deuteron threshold and is seen as the low-energy proton peak. If the high-energy proton peak were to correspond to the "ground state" it should thus be 16.69 Mev higher, rather than about 16.0 Mev as observed (but with an uncertainty too large to allow distinguishing between these two values).

This leaves the possiblity that the protons may depart with less energy and, consequently, that the neutron may later depart from the alpha with a greater energy than that corresponding to the "ground state." Assume that the proton is snatched out from its zero-momentum region just as the two nucleons of the deuteron cluster are at the end of their swing and turning back toward each other. The neutron is left outside the alpha at an uncertain distance corresponding to its distribution in the cluster model and thus considerably larger than usual shell-model radii. It is unbound, having suddenly lost its interaction with the proton, and its uncertain position and lack of angular momentum should be described by a wave packet somewhat like a virtual s state, having small amplitude within the alpha and a maximum at perhaps 2 or 3 times the radius of the alpha, because of the relatively large size of the cluster model. This uncertainty of position corresponds to a kinetic energy of only a few Mev to be carried away by the departing neutron. The shape of the peak in the observed proton spectrum may thus correspond to the energy distribution required by the uncertainty principle in view of the particle distribution in the cluster model. Further $(p,2p)$ observations with higher resolution may thus reveal interesting geometrical details of Li^6.

PHYSICAL REVIEW VOLUME 126, NUMBER 5 JUNE 1, 1962

Low-Energy Neutrons from the Reaction $Be^9(\alpha,n)C^{12}$ *

F. A. St. Romain, T. W. Bonner,† R. L. Bramblett, and J. Hanna
Rice University, Houston, Texas
(Received December 18, 1961)

Experiments carried out on the detection of slow neutrons from the (α,n) reaction in Be^9 show an increasing number of low-energy neutrons beginning at an alpha particle energy of 4.3 Mev, and extending to 5.6 Mev. The energies and angular distribution of these neutrons for $E_\alpha=4.92$ and 5.11 Mev have been measured using the polyethylene sphere-moderated neutron spectrometer. The results indicate a peaking in the forward direction and an energy distribution consistent with their origin from inelastic alpha-particle scattering leaving Be^9 excited to the level at 1.75 Mev, which subsequently breaks up with neutron emission. At an alpha-particle energy of 5.11 Mev, the mean energy of these neutrons and the differential cross sections are: 0°(0.33 Mev, 22 mb/sr); 70°(0.21 Mev, 8 mb/sr); and 120°(0.07 Mev, 2 mb/sr). The neutron spectrum of a Pu-Be source has been determined to have a large number of low-energy neutrons with a peak intensity at 0.3 Mev.

INTRODUCTION

The (α,n) reaction with Be^9 has been studied extensively both with natural radioactive sources[1] and more recently with helium ions from a Van de Graaff accelerator.[2] The total yield of neutrons at 0° and 90° has been measured by Bonner, Kraus, Marion, and Schiffer[2] from 1.5 to 5.3 Mev. The cross section and angular distributions of the neutrons leading to C^{12} in the ground state and the first excited state have been measured by Risser, Price, and Class.[3] Recently the cross sections and angular distributions have been studied for three groups of neutrons including those which leave C^{12} in its second excited state at 7.66 Mev.[4]

The present experiment was undertaken to search for the threshold of neutrons to the 7.66-Mev state and to study the low-energy neutrons that had previously been observed in this laboratory when alpha particles with energies greater than approximately 4.3 Mev struck a thin beryllium target.

EXPERIMENTAL PROCEDURES

The counter ratio technique[5] was used to detect the presence of "threshold-neutrons" in the presence of high-energy neutrons. Data were taken with two counters simultaneously, one placed directly behind the other. The forward or "slow counter" was a Li^6I scintillator at the center of a 3-in. polyethylene moder-

* Supported in part by the U. S. Atomic Energy Commission.
† Deceased.
[1] I. Halpern, Phys. Rev. **76**, 248 (1949); R. L. Walker, Phys. Rev. **76**, 244 (1949); B. G. Whitmore and W. B. Baker, Phys. Rev. **78**, 799 (1950); J. D. Elliot, W. I. McGarry, and W. R. Faust, Phys. Rev. **93**, 1348 (1954); L. Stewart, Phys. Rev. **98**, 740 (1955); H. W. Broek and C. E. Anderson, Rev. Sci. Instr. **31**, 1063 (1960).
[2] T. W. Bonner, A. A. Kraus, J. B. Marion, and J. P. Schiffer, Phys. Rev. **102**, 1348 (1956).
[3] J. R. Risser, J. E. Price, and C. M. Class, Phys. Rev. **105**, 1288 (1957).
[4] T. Retz-Schmidt, T. W. Bonner, G. U. Din, and J. L. Weil, Bull. Am. Phys. Soc. **5**, 110 (1960); F. Ajzenberg-Selove and P. H. Stelson, Phys. Rev. **120**, 500 (1960).
[5] T. W. Bonner, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960).

TABLE I. Ratio of counting rates in the detectors with diameters of 2, 3, 5, and 12 in. The calculated ratios are for (A) neutrons leading to the formation of C^{12} in the ground state and the first two excited states and (B) the same plus a group of low-energy neutrons with the energy and intensity given in Table II.

	3/2			5/2			12/3			12/5		
	0°	70°	120°	0°	70°	120°	0°	70°	120°	0°	70°	120°
				$E_\alpha=4.917$ Mev								
Calculated (3 groups)	9.24	8.85	7.25	55.1	50.0	40.7	14.2	11.3	7.97	2.34	2.01	1.34
Experimental	6.52	6.46	6.57	28.0	25.0	29.8	6.78	5.22	6.15	1.58	1.36	1.36
Calculated (4 groups)	6.53	···	···	26.8	···	···	6.73	···	···	1.64	···	···
				$E_\alpha=5.109$ Mev								
Calculated (3 groups)	9.12	8.97	8.49	55.9	52.2	43.5	14.9	12.3	7.70	2.43	2.11	1.43
Experimental	6.06	5.00	6.15	23.6	19.4	25.6	5.41	4.84	5.43	1.40	1.25	1.30
Calculated (4 groups)	6.16	5.59	6.11	23.4	20.2	25.7	5.41	4.74	5.48	1.43	1.32	1.30

ating sphere, and the fast counter was of the same type except that the diameter of the moderating sphere was 8 in. The two counters were placed at zero degrees to the alpha-particle beam, one directly behind the other, and at such distances that they both subtended a half angle of 20°. Because of the relative sensitivities of the two counters for neutrons of different energies, an increase in the ratio of the counting rate of the 3-in. counter as compared to that in the 8-in. counter indicates an increase in the relative number of low-energy neutrons. Experiments were carried out with this arrangement for alpha-particle energies of from 2.3 to 5.57 Mev with a beryllium target with a thickness of 35 μg/cm^2.

In the second part of this experiment the same type of detector[6] was used with moderating spheres with diameters of 2, 3, 5, 8, and 12 in. The counters were positioned at three laboratory angles of 0°, 70°, and 120° and data were obtained at alpha-particle energy of 4.917 and 5.109 Mev with a beryllium target which had a thickness of 68 μg/cm^2. The counting rate per microcoulomb of charge for each counter was determined with the counter so placed that it subtended a half angle of 16.7°. Data were taken at these angles because of the fact that the cross sections for the production of neutrons leading to the ground state and 7.65-Mev state (both 0^+ states) exhibit minima at these angles at both 4.917 and 5.109 Mev.[4] These energies were chosen because there is a minimum in the yield of neutrons from these two groups of neutrons in the region near 5.0 Mev. Under these conditions, the contributions of these two groups of neutrons to the counting rate in each of the counters are minimized, and most of the high-energy neutrons are due to those leaving C^{12} in the 4.43-Mev state.

EXPERIMENTAL RESULTS

$Be^9(\alpha,n)$ Spectra (Thin Target)

The results of the data obtained with the 3-in. and 8-in. sphere moderating counters, positioned one behind the other, are given in Fig. 1. Both counters show the well-known resonance at 2.6 Mev and 4.0 Mev, and the larger counter also shows broad resonances at 4.25, 4.95, 5.3, and 5.7 Mev. The neutron threshold calculated to be at an energy of 2.812 Mev was not detected, and this indicates that the cross section near threshold for this group of neutrons leaving C^{12} in the 7.65-Mev state is small in comparison to the total yield of neutrons.

Above approximately 4.3 Mev the counting rate in the 3-in. detector shows a progressive rise relative to that in the 8-in. counter. This indicates an increase in the number of low-energy "threshold neutrons," but the continued increase in this ratio from 4.3 to 5.6 Mev indicates a very broad state in C^{12} or another process such as $Be^9(\alpha,\alpha')Be^{9*}\rightarrow Be^8+n$ which continues to give low-energy neutrons over a wide range of alpha-particle energies. These data are consistent with either the emission of low-energy neutrons leaving C^{12} in the 10.1-Mev state which is 2 Mev wide or to the breakup of the excited state of Be^9 at 1.75 Mev. The second part of this experiment was undertaken to distinguish between these two possibilities.

Experiments to determine the energy and number of the "low-energy neutrons" were carried out with the neutron spectrometer[6] using five different sphere moderating detectors placed at distances of 10.0, 15.1, 25.0, 40.1, and 59.8 cm so that each counter subtended the

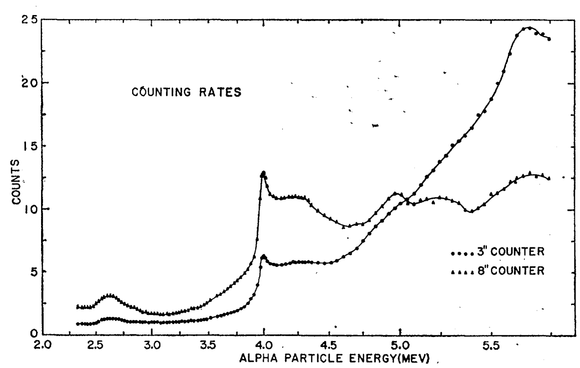

FIG. 1. The counting rate obtained in neutron counters as a function of the energies of alpha particles incident on a thin beryllium target. The 3-in. counter is selectively sensitive to low-energy neutrons while the 8-in. counter has a higher sensitivity for neutrons with energies greater than 1 Mev.

[6] R. L. Bramblett, R. I. Ewing, and T. W. Bonner, Nuclear Instr. and Methods 9, 1 (1960).

TABLE II. Energy and differential cross section of the fourth group of neutrons calculated from experimental ratios, assuming a monoenergetic fourth group.

	$E_\alpha=4.917$ Mev		$E_\alpha=5.109$ Mev					
	0°		0°		70°		120°	
Ratio	E_n (Mev)	Cross section (mb/sr)	E_n (Mev)	Cross section (mb/sr)	E_n (Mev)	Cross section (mb/sr)	E_n (Mev)	Cross section (mb/sr)
3/2	0.33±0.05	15	0.30±0.04	21	0.21±0.02	8	0.07±0.02	2
5/2	0.36±0.04	16	0.35±0.03	24	...	...	...	...
12/3	0.32±0.05	15	0.32±0.04	22	...	...	...	...
12/5	0.36±0.04	16	0.34±0.03	23	0.21±0.02	8	0.07±0.02	2
Average	0.34±0.05	16	0.33±0.03	23	0.21±0.02	8	0.07±0.02	2

same solid angle at the target. The relative counts per microcoulomb for each of the detectors was obtained to an accuracy of approximately 1%. These data were then multiplied by the appropriate geometrical factor to give the counts per microcoulomb at 40 cm. The ratio of these experimental counting rates at 40 cm distance are the basis of the energy analysis[6]; these ratios are given in Table I. Also tabulated are the calculated ratios for the first three groups of neutrons, using the cross sections[4] that have been obtained in other experiments. At the 120° angle where direct results were not obtained the angular distributions of the neutrons leading to the 7.65-Mev state are assumed to be the same as those of neutrons to the ground state. This assumption agrees with the results of Ajzenberg-Selove and Stelson[4] obtained at an alpha-particle energy of 5.6 Mev. The principal uncertainty in the intensity of the first three groups of neutrons is that of the third group, which is estimated to have a possible error of ±25%. The error in the calculated ratios due to this uncertainty amounts to 0.3%, 0.3%, 1.1%, and 0.5%, respectively, in the counter ratios of 12/5, 12/3, 5/2, and 3/2.

The data given in Table I show considerable deviations between the experimental ratios and calculated ratios at all angles except 120°. The difference in the ratios is an indication of the relative intensity of the fourth group of low-energy neutrons which has not been included in the calculated ratios. The data were first analyzed on the assumption that the low-energy neutrons are a monoenergetic group. If this fourth group is assumed to have a particular value of energy, an intensity corresponding to that energy can be calculated such that the experimental counting rate of the 12-in. counter to the 2-in. counter agrees with the experimental ratio. Using this energy and intensity, other ratios for the different detectors can be calculated and compared with the experimental results. By systematically varying the assumed energy and comparing the results with experiment, it was found that the results could be explained within the experimental error at each of the angles of observation. These results are given in Table II and are consistent with a monoenergetic group of neutrons within the experimental error. Results at $E_\alpha=4.917$ Mev include only the data at 0°, which are more accurate than those obtained at 70° and 120°. Results at $E_\alpha=5.109$ Mev at 70° and 120° include only the most sensitive ratios: 3/2 and 12/5. The experimental errors listed in the table are the differences between the energies predicted by ratios 1% above and 1% below the experimental ratios. The calculated counter ratios: 12/5, 5/2, and 3/2, including this fourth group of neutrons, are given in Table I. The agreement with the experimental data is good.

It is interest to note that, within the experimental error, the energy of the fourth group of neutrons when observed at 0° does not change with an increase of bombarding energy of 0.192 Mev. This result indicates that the neutrons are not emitted when C^{12} is left in a well-defined energy state. The data are most accurate at 0° and at the value of $E_\alpha=5.109$ Mev where the cross section is largest. The results at different angles are given for $E_\alpha=5.109$ Mev; a strong peaking in the forward direction is found. The cross section of 22 mb/sr at 0° for the fourth group is of the same order of magnitude as that to the ground state and first excited state which have cross sections of 4 mb/sr and 75 mb/sr, respectively. Even with the forward peaking, the total cross section of this group, integrated over all angles, is about the same as that of the ground-state group and only a factor of about five smaller than that of the second group of neutrons.

Analysis was also carried out to test whether the low-energy neutrons could have their origin in the broad state in C^{12} at 10.1 Mev with a width of 2.0 Mev. The calculated ratios could not be made to agree with the experimental ratios at 0° and 70° with such a wide state. Since the width of this state is not known accurately, attempts to fit the experimental ratios were made with smaller widths. Consistent results were not obtained for any width of a broad state in C^{12}.

Interpretation of the experimental results has been made on the basis of the low-energy neutrons originating from inelastic scattering of alpha particles leaving Be^9 excited to the states at 1.75 Mev and 2.43 Mev. The excited Be^9 then decays by neutron emission and the energies of the neutrons are strongly influenced by the recoil motion of the Be^9. It is further assumed that for $E_\alpha=4.92$ and 5.11 Mev, most of the neutrons originate in the decay of the 1.75-Mev state.

The calculation of the neutron energy distribution due to the above process would require detailed knowledge of the angular distribution of the inelastically scattered alpha particles and the angular distribution of neutrons emitted from the excited Be^9 nucleus. However, the maximum and minimum neutron energies can be calculated. The maximum center-of-mass velocity occurs when the alpha particle is scattered backward. In this case the maximum neutron energies of 0° are 0.74 and 0.77 Mev for alpha-particle energies of 4.92 and 5.11 Mev. Neutrons emitted backward in the center of mass still come forward with energies of 0.087 and 0.098 Mev. Under these conditions all the neutrons are in the forward direction within a small cone. If the alpha particle is inelastically scattered through a small angle very little recoil velocity is imparted to the Be^9. The mean energy of all of these neutrons produced by inelastic scattering to the 1.75-Mev state in Be^9 is expected to be in the neighborhood of the experimental value of 0.33 Mev.

The results of Ajzenberg-Selove and Stelson[4] for $E_\alpha = 5.81$ Mev and angle of observation of 0°, indicate more neutrons with energies of 0.8 Mev than neutrons that leave C^{12} in the 7.66-Mev state. They observe a continuum of neutrons up to over 2 Mev. This result can be explained if a considerable portion of these neutrons are produced by inelastic alpha scattering leaving Be^9 in the excited state at 2.43 Mev as well as in the 1.75-Mev state. At their higher alpha-particle energy this channel is expected to become important. Neutrons with a maximum energy of 2.2 Mev are predicted by this process.

Neutron Spectrum of a Pu-Be Source

The neutron spectrum of a Pu-Be source was examined by the same method. The source which emitted 1.34×10^6 neutrons per second was placed at respective distances of 6.69-, 10.07-, 16.71-, 26.78-, and 40.0-cm from the 2-, 3-, 5-, 8-, and 12-in. counters. The experimental arrangement was such that the nearest scattering material was 12 ft away and consequently the room background was small enough so that it could be neglected. The experimental data were corrected for a small gamma-ray contribution from the 4.43-Mev gamma radiation and converted to the relative counting rates at the standard distance of 40 cm. The results are given in Table III and compared to that predicted by the neutron spectrum above 0.7 Mev, which has been measured by Stewart.[1] The results differ in some cases by more than a factor of two and indicate the presence of many neutrons with energies less than 0.7 Mev. The data have been fit by the Stewart spectrum above 0.7 Mev and the spectrum shown in Fig. 2 at lower energies. This assumed spectrum with a peak at 0.3 Mev agrees well with the experimental data; the peak at 0.3 Mev is expected from the results obtained in the first part of this experiment. The average energy of the Pu-Be neutrons for this spectrum is 4.2 Mev.

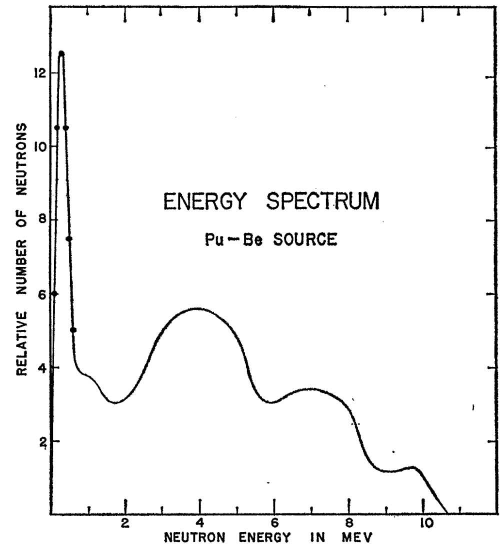

FIG. 2. The measured neutron spectra from a Pu-Be source. The data above 0.7 Mev are those obtained by Stewart.

TABLE III. Data with Pu-Be neutron source.

Counters used	12/2	12/3	12/5	8/2	8/3	5/2
Experimental ratios[a]	34.1	5.32	1.28	42.3	6.59	26.6
Calculated ratios, Stewart spectra above 0.7 Mev	79.5	9.31	1.75	88.5	10.4	45.5
Calculated ratios, spectrum of Fig. 2	34.4	5.30	1.30	42.1	6.48	26.5

[a] After subtraction of a gamma-ray contribution of 5% and 1%, respectively, in the 2- and 3-in. counters.